Tomo-Lithographic-Molding (TLM™) - A Breakthrough Manufacturing Process for Large Area Micro-Mechanical Systems

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Abstract **- Mikro Systems Inc. (MSI) has developed a high volume manufacturing process for producing complex, net-shape, micro-to-meso scale structures from advanced materials comprised of powdered metals, ceramics, and polymers. This process, called Tomo-Lithographic-Molding (TLM™), hinges upon a high-resolution master tool composed from lithographically micro-machined layers, precisely aligned and stack laminated into a monolithic solid. By combining dissimilarly patterned layers or "toma", 3D cavities of otherwise unattainable sophistication and precision can be created. Combining these disciplines with proprietary casting and forming methods enables the production of cost effective, high aspect-ratio devices and systems with features in the micro-to-meso scale. Thousands of micro-meso features in varied distributions and customized geometries can be arrayed upon large (square meter) planar or non-planar surfaces. These surfaces may, in turn, be used as plies in a macro-scale, laminate composite structure thus optimizing physical properties.**

I. INTRODUCTION

Mikro Systems Inc. (MSI) has developed a breakthrough manufacturing process for producing complex, large-area micro-mechanical systems (LAMMS). This process, called Tomo-Lithographic-Molding (TLM™), involves creating a high-resolution laminated master tool using lithographically derived, micro-machined layers and precision stack-lamination methods. Combining these disciplines with proprietary casting and forming methods enables the production of cost effective LAMMS with features in the micro-to-meso scale that can be arrayed over large (m^2 scale) planar or non-planar surface areas.

Through the use of TLM™, MSI has successfully produced state-of-the-art microwell neutron-detector arrays, sub-millimeter feedhorn arrays, x-ray and gamma-ray collimators and scatter reduction grids, radiation shielding containers and conformal intensifier screens used in solar and astrophysics, medical imaging, and industrial radiography. Materials have included metals, ceramics, and polymers depending on the application.

For x-ray and gamma-ray applications, a dense casting composite was developed using tungsten powder combined with a polymer binder. This important material development has provided an environmentally-safe alternative to current lead-based products. Material performance characteristics are equal or superior to lead. Through the combined use of powdered metal composites and TLM™, significant product breakthroughs have been realized and are currently being applied to scientific and commercial applications.

MSI has also applied the TLM™ process for use with powdered ceramic materials. Our goal is to overcome the limitations associated with current ceramic forming methods, which are limited in terms of feature size, part complexity, and production cost. Using TLM™ we have produced advanced ceramic structures with fine features (<30 microns), high-aspect ratios (>20:1) and complex 3-D geometries. Potential commercial markets for ceramics include energy, transportation, manufacturing, medical and information technologies.

The current paper describes utilizing the TLM™ process for production of patterned arrays of micro-to-meso scale features over large surface areas. TLM™-derived microstructures of engineered plastics and synthetic multifunctional materials are contemplated.

A. Background

During the last decade micro-electro-mechanical systems (MEMS) have emerged through the development of fabrication processes used for producing integrated circuits and microelectronics. Examples of early MEMS devices include sensors and actuators, which are fabricated from silicon and are integrated with and controlled by conventional microelectronics and circuits. Other less integrated MEMS devices have been developed such as micro-accelerometers, inkjet printer heads, and micro-mirrors that are more mechanical in function. More complex MEMS devices have been investigated and applied to such varied fields as aerospace, biomedical, chemical analysis, wireless communications, data storage, optics etc.

The primary approach used to fabricating MEMS devices includes the micro-machining of silicon, crystalline silicon, polycrystalline silicon and silicon nitride. These techniques have been effective in producing devices with feature sizes ranging from sub-millimeter to sub-micron in scale, but have been limited in terms of material selection, aspect-ratio, producing structures on non-planar surfaces, and being able to engineer and fabricate more complex three-dimensional devices. Techniques have been developed for manufacturing more advanced 3D MEMS devices made from materials other than silicon. These fabrication techniques include LIGA (a German acronym for lithography, galvanoforming, molding), stereolithography (SL), micro-stereolithography (MSL), micro-photo-forming, electrochemical fabrication, micro-transfer molding, layered object manufacturing (LOM), fused deposition modeling (FDM) and others. Although these techniques have greatly advanced MEMS technologies and devices, significant limitations still remain regarding cost-effective production of 3D micro devices from diverse materials, with high-aspect ratios, planar and non-planar surfaces, and particularly over large areas (greater than 0.25 m^2).

Achieving the latter would radically expand the ability to optimize the physical properties of macrostructures. The integration of Finite Element Analysis, genomic algorithms, and TLM make this goal feasible.

Finite Element Analysis techniques [1] can define the component forces acting upon each computational element of a macrostructure. If each element is treated as a discrete object, and the component forces acting upon each element are treated as discrete local forces, a custom microstructure can be designed to operate within this microenvironment. These "micro designs" can be cataloged and applied repeatedly to satisfy similar requirements. The aggregation of these micro-scale designs into a macro-scale design, such as a spacecraft skin panel, is the essence of a TLM™-enabled Large Area Micro Mechanical System. The cost effective fabrication of such intricate and complex structures is beyond the capability of conventional MEMS manufacturing processes.

II. DESCRIPTION OF THE TLM™ PROCESS

The following sections provide a brief description of the TLM™ process, highlighting some of the aforementioned advantages, and offering some insights into the flexibility and application of this process.

A. TLM™ Process Overview. Essentially, TLM™ is layered object manufacturing turned inside out. A master tool - a mold or embossing / blanking die – embodies an array of microcavities which, in aggregate, is the inverse configuration of the final part. Each microcavity can embody any number and configuration of undercuts and blind features that would otherwise be impossible to produce in a single operation. This master tool is employed in "cookie cutter" fashion to mass produce intricate monolithic microstructures.

One of the principal economic advantages of the TLM™ process is its use of low cost, non-perishable master tooling from which additional perishable tools may be derived, or parts may be produced directly. The master is typically made from a durable metal and may be coated with an application-specific material to enhance performance. Because this is a nonrecurring operation, high volume production and attendant economies of scale are facilitated. Downstream operations do not require sophisticated clean room facilities or elaborate process control technology. TLM™ is a robust manufacturing process. Figure 1 illustrates the basic sequence of operations.

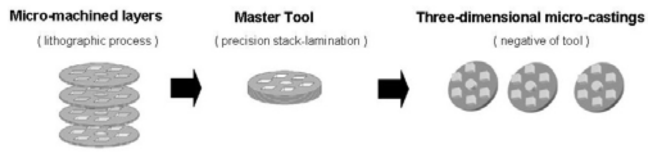


Figure 1. Simplified TLM™ Process

The master tool can be produced as a negative or positive of the desired finished product. The three critical process steps needed to create the master tool are shown in **Figure 2**.

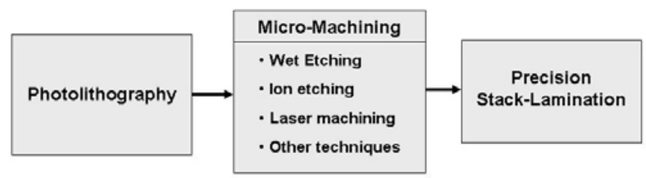


Figure 2. Critical Process Steps

1) Lithographic Techniques: Using lithography as a means of layer fabrication is advantageous to many aspects of microstructure design. Individual features (micro-structures) can be designed as an aggregation of diameters, squares, rectangles, hexagons, or any other shape or combination of shapes in a Cartesian (X-Y) plane. The combination of any number of different shapes and distributions enables the production of non-redundant design arrays (i.e., patterns in which not all feature shapes and/or sizes are identical). Each pattern and its associated microstructures can be customized to satisfy local design requirements. Thus, for example, a large cylindrical pillar may be situated in the midst of a field of tripods, all surrounded by corrugated hexagonal posts.

The lithographic process is capable of maintaining strict dimensional tolerances because each layer is derived from a photographic mask. Geometric accuracy pertains to both line-width resolution and positional accuracy of the plotted features over the desired area. This enables both micro-scale fabrication and subsequent integration of micro-mechanical and micro-electronic devices into Large Area MEMS.

2) Micro-Machining and Material Options: The particular technique or techniques used to machine or mill out the features and patterns from the layer material is an important aspect of fabricating the master tool. By combining lithographic imaging and micro-machining techniques, additional degrees of freedom are afforded the designer of high-aspect-ratio, 3D structures. Mikro Systems refers to this enhanced capability as "design-agility". Some of the micro machining processes that can be used to fabricate layers (typically metal foils) for the master tool include photo-etching, laser machining, reactive ion etching, electroplating, vapor deposition, bulk micro-machining, surface micro-machining, conventional machining, or a combination of these methods. Concomitant with the expanded repertoire of processes is an expanded menu of materials from which the master tool can be constructed. Because master tool fabrication is a nonrecurring step of the TLM™ process, tool material(s) can be selected primarily on the basis of tool performance criteria and secondarily on the basis of cost. This introduces the opportunity to further optimize tool performance. For example, thinner foils and/or foils of dissimilar materials in different positions within the stack lamination is possible. Since foil thickness is a primary determinant of feature size, thinner foils can embody finer features which, in turn, result in finished parts with finer and more accurate features.

The practice of using multiple micro-machining techniques further expands design and fabrication options. Any given layer might be produced with a combination of micro-machining processes; each process being employed to create specific features. An example of this would be to use photo-chemical-machining for larger features and high resolution ion-etching for finer features.

3) *Precision Stack-Lamination:* As mentioned above, layers are designed and produced so that microstructure shape and position from layer to layer define the desired geometry in the x-, y-, and z-axis. The total number (and thickness) of layers in the assembly defines the overall height and aspect ratio of the microstructure. The alignment of layers and microstructures in the assembled master tool are critical when considering the scale of the device or microstructures being produced. Mikro Systems has used two different methods of bonding the layers together to form the master tool: 1) metal-to-metal brazing, and 2) epoxy bonding. Each technique has advantages for certain applications.

B. Master tools: Master tools can be made as negatives or positives of the finished part configuration. As shown in **Figure 3**, if the master is made as a negative, the finished part may be produced directly from the tool. If the master is made as a positive, it will be necessary to create a second-generation (or derived) master. Some production situations would require a second (or even a third) generation version of the master tool. Downstream process parameters and control limits are primary design factors when contemplating the configuration (positive or negative rendition of the finished part) of the master tool. If, for example, the finished part is made of a flexible material having good release properties, a rigid master tool could be used, whereas, if the finished part was very rigid, with poor release properties, a second-generation consumable master tool could be used.. To-date, Mikro Systems has used three main types of masters: 1) rigid tools made of metal or ceramics, 2) flexible tools made of rubber or various polymers, and 3) consumable tools, made of wax or consumable polymers.

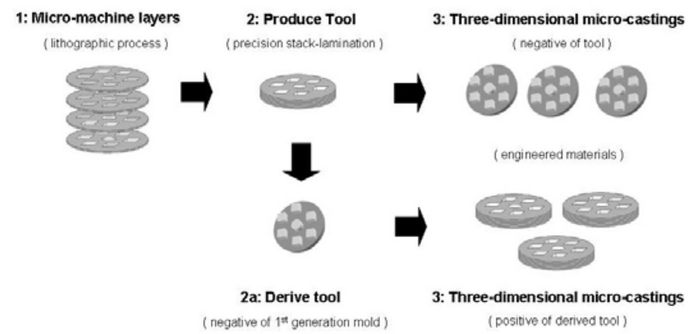


Figure 3. 1st and 2nd Generation Molds

C. Production Methods: In recent years, numerous processes have been developed or optimized for producing micro-devices and structures. All of these processes, by degrees, are production volume constrained in the sense that each part is produced individually or in small batches, often with numerous intermediate steps involving the deposition and removal of sacrificial material. TLM™ is the only process by means of which high volume, batch manufacturing of MEMS is feasible. Moreover it is the only process that is compatible with continuous flow manufacturing methods.

High volume batch production of microdevices can be realized by creating a uniform array of devices across a sacrificial backplane. Thousands of devices can be created in a single operation. The devices can be parted from the backplane as individual items or in sets.

There are many technologies and companies producing equipment for the varied methods used for micro-fabrication. Some of the methods used for micro-molding and casting are microinjection molding, powder injection molding, metal injection molding, photo molding, hot embossing, micro-transfer molding, jet molding, pressure casting, vacuum casting, and spin casting. Each of these methods could make use of tooling produced by the TLM™ process.

D. Materials: As mentioned earlier, most MEMS fabrication techniques are limited to silicon-based materials, since the manufacturing processes are primarily derived from the microelectronics industry. One of the most important attributes of the TLM™ process is the ability to produce parts in a number of different materials. Mikro Systems Inc has used the TLM™ process to fabricate parts using three types of materials to-date: 1) powder metals (such as tungsten, copper, and gold), 2) powder ceramics (such as alumina and zirconia), and 3) polymers (such as silicone rubber, urethanes, and epoxies). We also have investigated combinations of materials (such as ceramic and metal powder / epoxy composites).

III. Comparison with Other Processes

The MEMS processes mentioned in the preceding *Background* section are specifically directed towards the production of advanced three-dimensional structures and devices. The primary reason for citing these particular processes is the common use of layered fabrication. TLM™ makes use of layering for the fabrication of tools and 3D MEMS structures. While each of the cited processes have been proven effective in creating 3D microstructures, TLM™ is the only process to date that allows more sophisticated design and control of features in the third (Z-axis) dimension, affords the option to work in different materials, and very importantly, allows 3D microstructures to be arrayed over large planar or contoured surface areas. The process also has an expansive breadth of scale and is capable of producing meso-scale structures that are impossible or impractical to produce with any other technology. **Figure 4** provides a comparison of TLM™ with other MEMS fabrication processes.

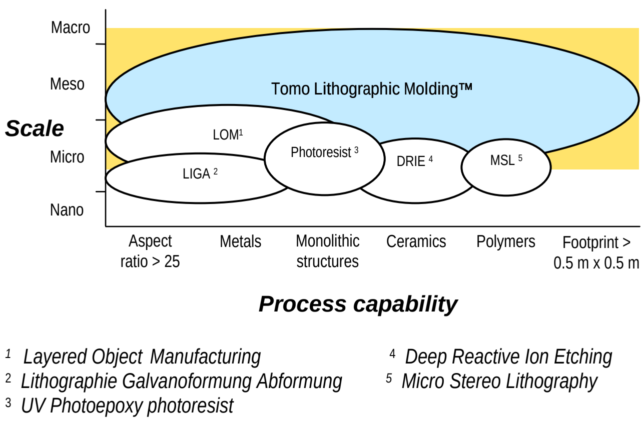


Figure 4. MEMS Process Comparison

Thus far, this paper has concentrated on the relative advantages of TLM™ with respect to a mono ply or single surface area. We now introduce the concept of joining multiple plies into intrinsically smart, composite structures wherein the microstructures of each ply are integrated with one another. Application-specific materials or combinations of materials (synthetic composites) can be employed to perform functions such as sensing strain, stress, temperature, and/or vibration dampening [2] [3] [4].

The TLM™ process facilitates simplified product designs; undercuts and blind features can be designed into monolithic structures, thus avoiding assemblies of parts. This reduces the opportunity for defects and promotes product quality.

The process is compatible with continuous flow manufacturing practices and is readily scalable. A master tool or series of tools can perform progressive operations such as continuous flow injection molding, embossing, blanking and bonding. Economies of scale can be realized sooner by virtue of the relatively low capital costs to implement TLM™ and lower recurring costs. The need for clean room facilities is obviated, master tools can be replicated at low cost, and implementation schedules can be compressed. The ability to produce tools at an accelerated pace is particularly advantageous to rapid prototyping programs.

The relative simplicity of TLM™ fosters process reliability which is manifest in high product yields and high availability of production equipment (i.e., long meantime between maintenance cycles). The process can be automated in a simple and innovative manner that affords the opportunity to further increase production capacity and lower direct labor costs. Altogether, TLM™ is a robust manufacturing process that can be operated within strict process control limits. High yields, high capacity, high availability of production assets result in low unit cost.

IV. APPLICATION EXAMPLES

The following examples have been selected to illustrate several major attributes of the TLM™ process: Example 1 demonstrates the use of TLM™ to array precisely angled micro-scale features across a macro-scale surface. Examples 2 and 3 demonstrate production of more complex 3D features. For demonstration purposes, each example has been produced in a single-ply configuration using a casting process .

In the first example a precision TLM™ mold was fabricated having 131,589 cylindrical shape cavities arrayed over a 45 centimeter diameter surface. The cavities are 0.950 millimeters in diameter, have a depth of 3.25 millimeters, and are arrayed in staggered rows and columns to maximize the pattern density. The pitch frequency of the cavities is 1.00 millimeter.

The arrayed pattern is comprised of four identical quadrants located around a central x, y datum. The cavity located at the center of the array is perpendicular to the mold surface at an angle of 90 degrees (datum cavity). The remaining cavities in each quadrant of the mold are uniquely angled relative to the mold surface. A cumulative angle of 0.01196 degrees was applied to each cavity position within each quadrant (1.00 millimeter pitch) resulting in a focused cavity array with each cavity pointing precisely at a predetermined focal point. The focal point of the array was centered on the datum cavity at a distance of 5 meters.

Using a vacuum assisted casting process, a LAMMS device was derived from the TLM™ mold using a high strength poly-urethane resin. The cast resin part and the TLM™ mold were dimensionally characterized and compared for accuracy. The measurements were made using an Accugage AG24 video metrology system.

Figure 5 shows an overall view of the micro-structure array and to the right a magnified view (the small divisions on the scale are 1mm).

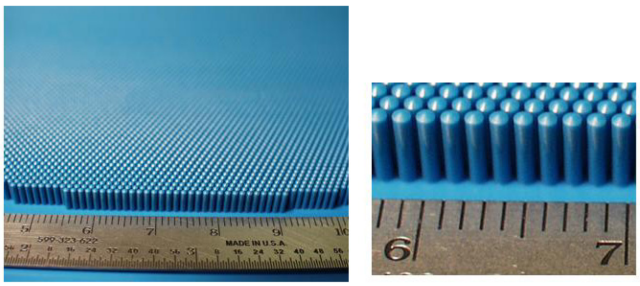
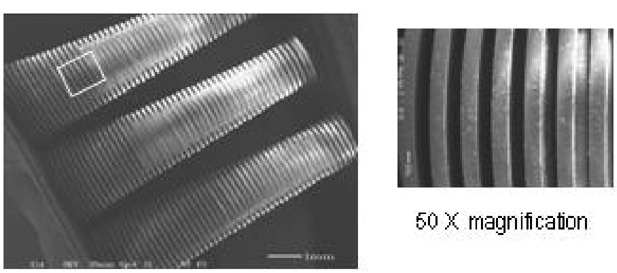


Figure 5. Micro-scale Features on Macro-scale Surface

This example demonstrates the ability to produce a precision micro-structure array over a large area using a TLM™ mold. Each feature in a quadrant of the array has a unique x, y and z orientation, but the individual structures are somewhat simple and repetitive in terms of shape. Examples 2 and 3 are presented to show how more complex features within an array can be produced using the TLM™ process.

The second example, shown in **Figure 6**, was chosen to illustrate a micro-structure array designed to increase the surface area of a single structure by a factor of four. The structures are tapered columns with corrugated ridges forming precise slots in the Z axis. The high-surface area columns were derived from a TLM™ mold using a platinum cure silicone rubber. The TLM™ mold was fabricated using photo-chemically etched, 75 micron thick copper foils which were precision stack laminated. The foils were bonded using a high-strength, thermal cure epoxy.



50 X magnification

Scale: 1 mm; 14 X magnification

Figure 6. High-Surface Area Micro-Columns

This high-surface area micro-structure has the following dimensional characteristics:

- 1020 arrayed 3D micro-columns
- 75 x 75 millimeter array area
- 54 circular slots on each column
- 75 micron width x 215 micron deep slots
- Column height 8.3 mm

Another example involving complex 3D structures is shown in **Figure 7**. This was produced using a TLM™ mold comprised of six photo-chemically machined stainless steel layers. Each layer in the mold had a thickness of 150 microns. The layers were laminated together using a eutectic CuSil™ (copper / silver) metal brazing process. The mold was designed to survive high-volume molding using a high-strength, flexible polymer casting resin to form the final part.

Figure 7 shows a magnified view of the cast 3D structures. A square-shaped structure was chosen for this example to further demonstrate the versatility of lithography.

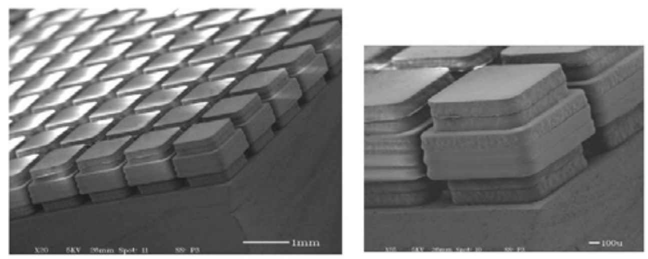


Figure 7. Cast Polymer Micro-Structure

- Cast Polymer Micro-Structures
- Micro-Structure Array = 20 x 60
- Top and Bottom Surface 870 x 870 microns
- Center Surface 1.035 x 1.035 mm
- Micro Structure Height 900 microns

References

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